Near Term Fission-Fusion Hybrids

Status and recent results

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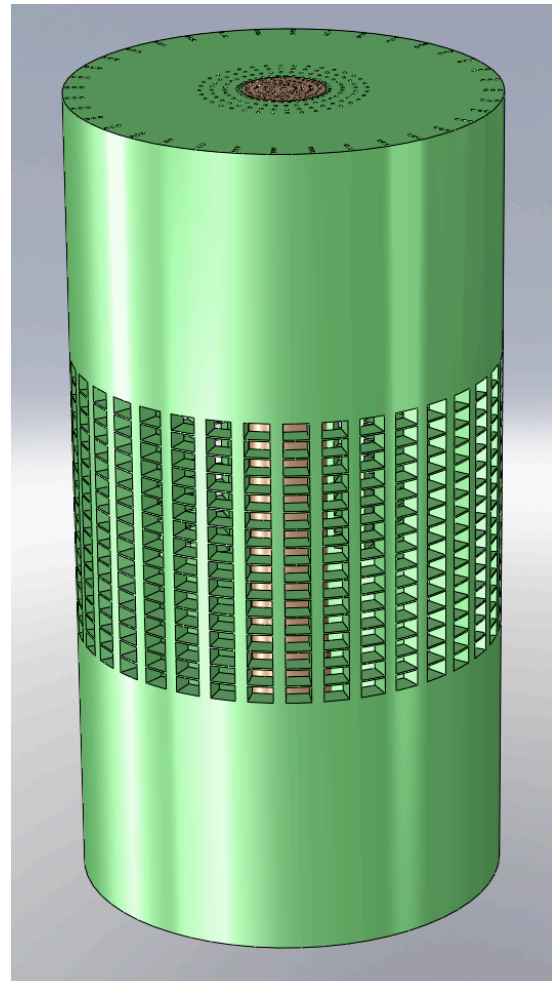


Fusion Augmented Fission

- There is a history of invoking External neutrons to help fission's achieving fuel cycle
- Strong incentive to design a desirable fusion neutron source - much nearer term than a pure fusion reactor.

- Fusion research, though far from leading to a net power producing commercial reactor, has made tremendous strides- enough that the fusion Component Test Facility (CTF)- presently slated for 2020's- is quite near what could be the basis of a desired neutron source for a hybrid

- It took three innovative ideas to design -

  a compact high power density fusion neutron source (CFNS)

  and then integrate fusion and fission systems

so that the hybrid, a combination of two advanced complicated technologies, is viable, and near term doable

Focusing on the fusion part

- Since there is vast experience and body of knowledge in fission, and the neutron source is the "sine qua non" of the hybrid, we shall concentrate primarily on the neutron source

- Choice of fission cycles is, indeed, crucial- some new, and some borrowed from the literature, are being examined. *Naturally we are seriously looking at fuel cycles that favor implementation through external neutrons.*

- But first things first- We begin with conceptual design of the Compact Fusion Neutron Source (CFNS).

Three Novel Concepts for nearer term hybrid

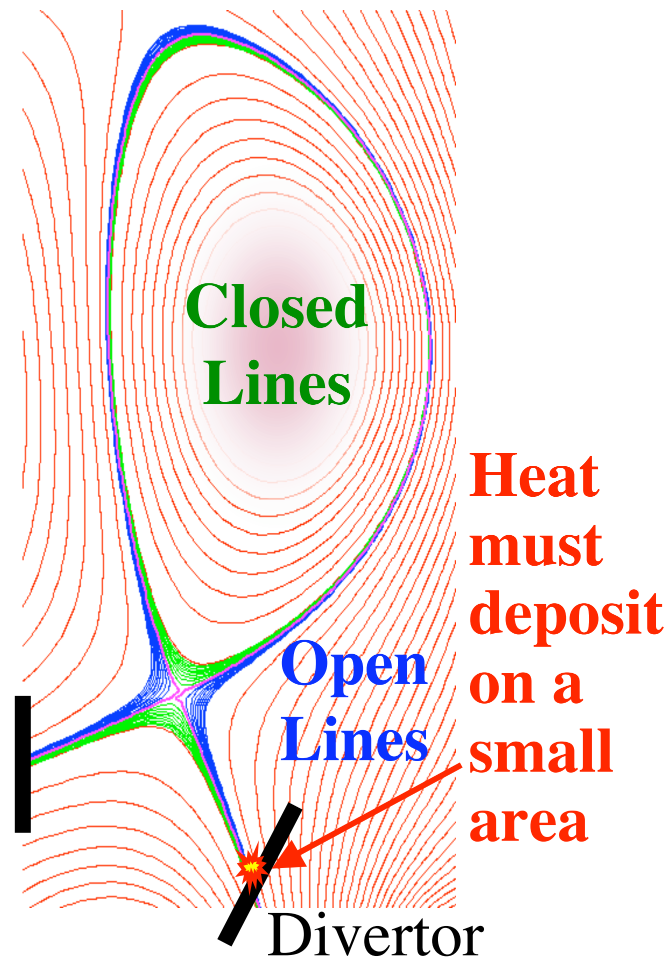
1. Invention of a new magnetic geometry (the Super-X divertor) to solve the formidable power exhaust problem characteristic of the high power density fusion. *Allows a Compact Fusion Neutron Source (CFNS) with a power density roughly five times higher than ITER*

2. Compactness and low weight allows the CFNS (< 300 tons) to be used as a *replaceable module* inside the fission blanket

3. Consider fuel cycles that greatly increase the hybrid's support ratio to thermal spectrum reactors (*~ 2-10 hybrids per 100 LWRs*)

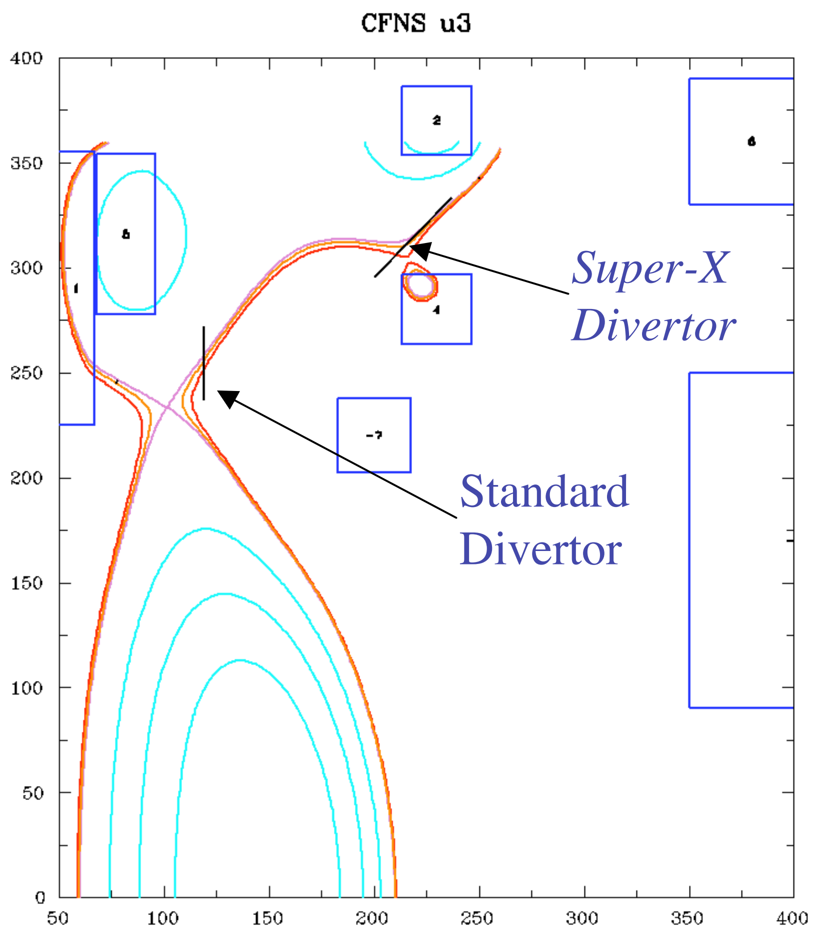
Compactness => High power density => exhaust bottleneck

- Tokamaks have the experimental/theoretical basis to:
  - produce needed quantity of fusion power ~ 100-200 MW
  - To attain the requisite high power density in the closed field region
- The primary limit to power density in a compact tokamak: power is exhausted onto a small area called the divertor
- This implies a heat flux “bottleneck”

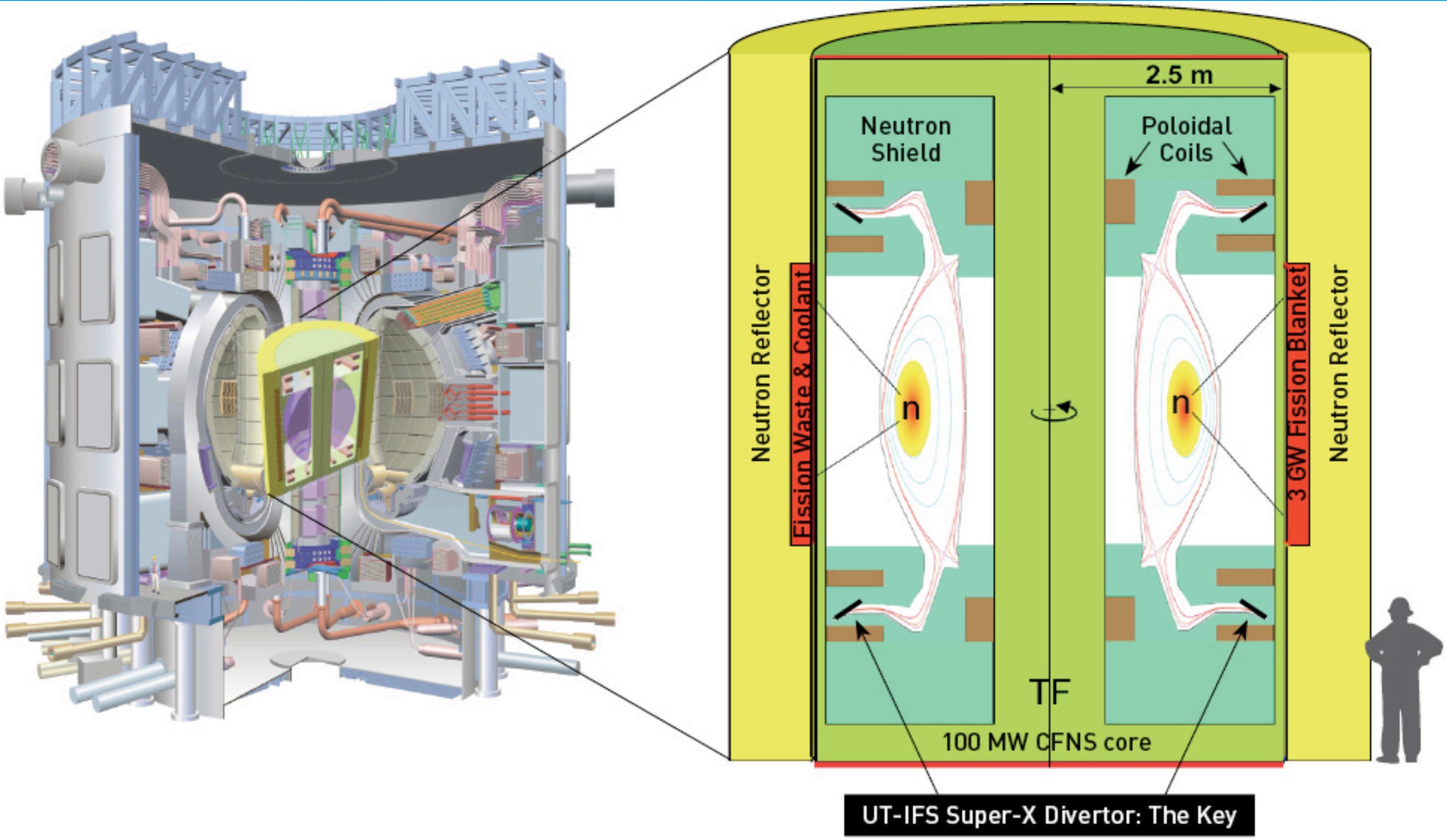


Super-X divertor solves the exhaust problem
Enables a compact high power density CFNS

- *Super-X Divertor (SXD)-* Field lines direct the exhausted plasma power to the divertor plate at larger major radius
  - *This allows exhaust to expand and cool to reach acceptable temperatures and heat flux*
- Experimental plasma device in UK recently received 30 million pounds (Sterling!) to implement and test the SXD



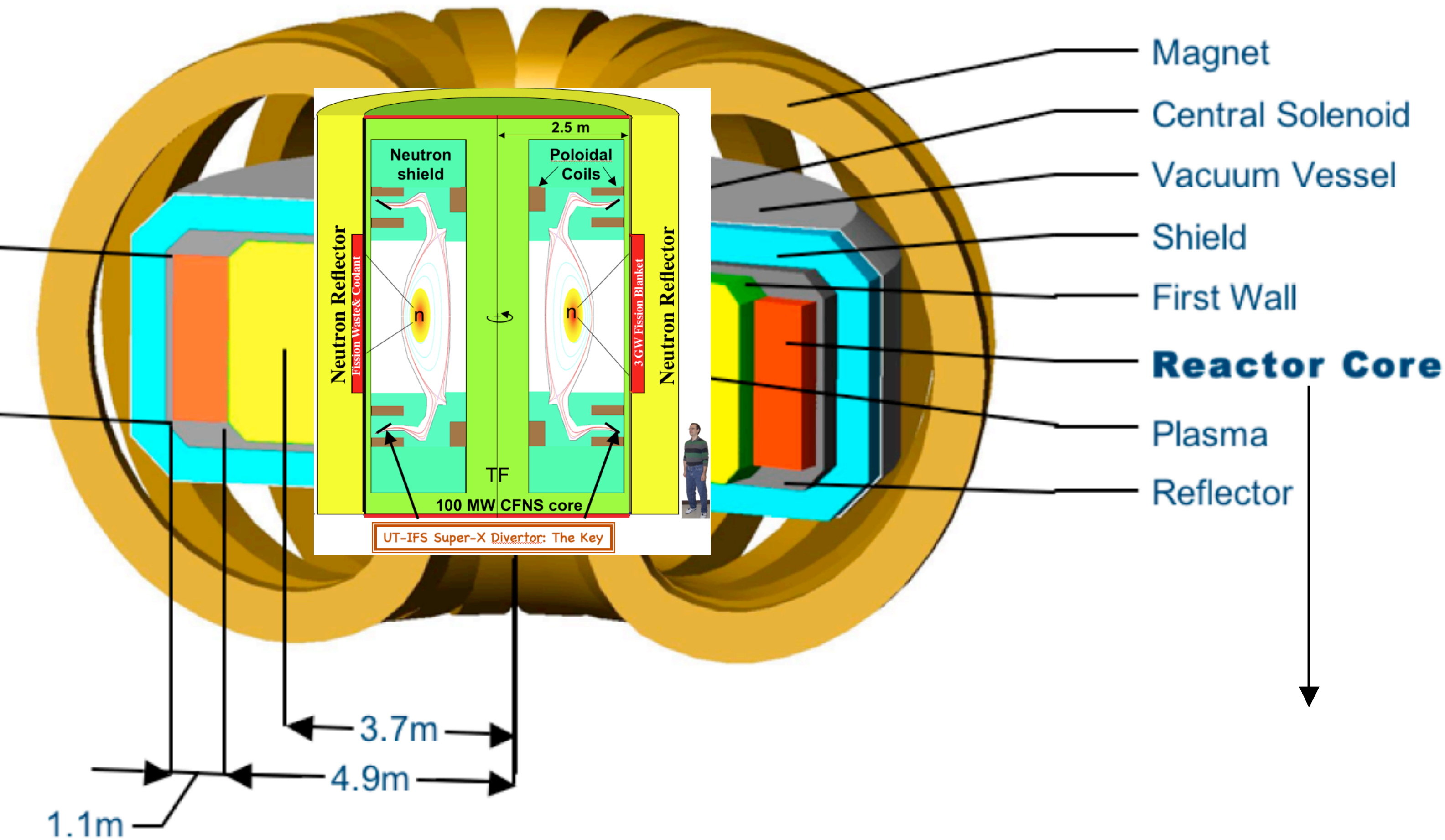
How compact is compact?



ITER (the next fusion flagship) and Hybrid (on same scale)

CFNS "Module" in Hybrid Reactor

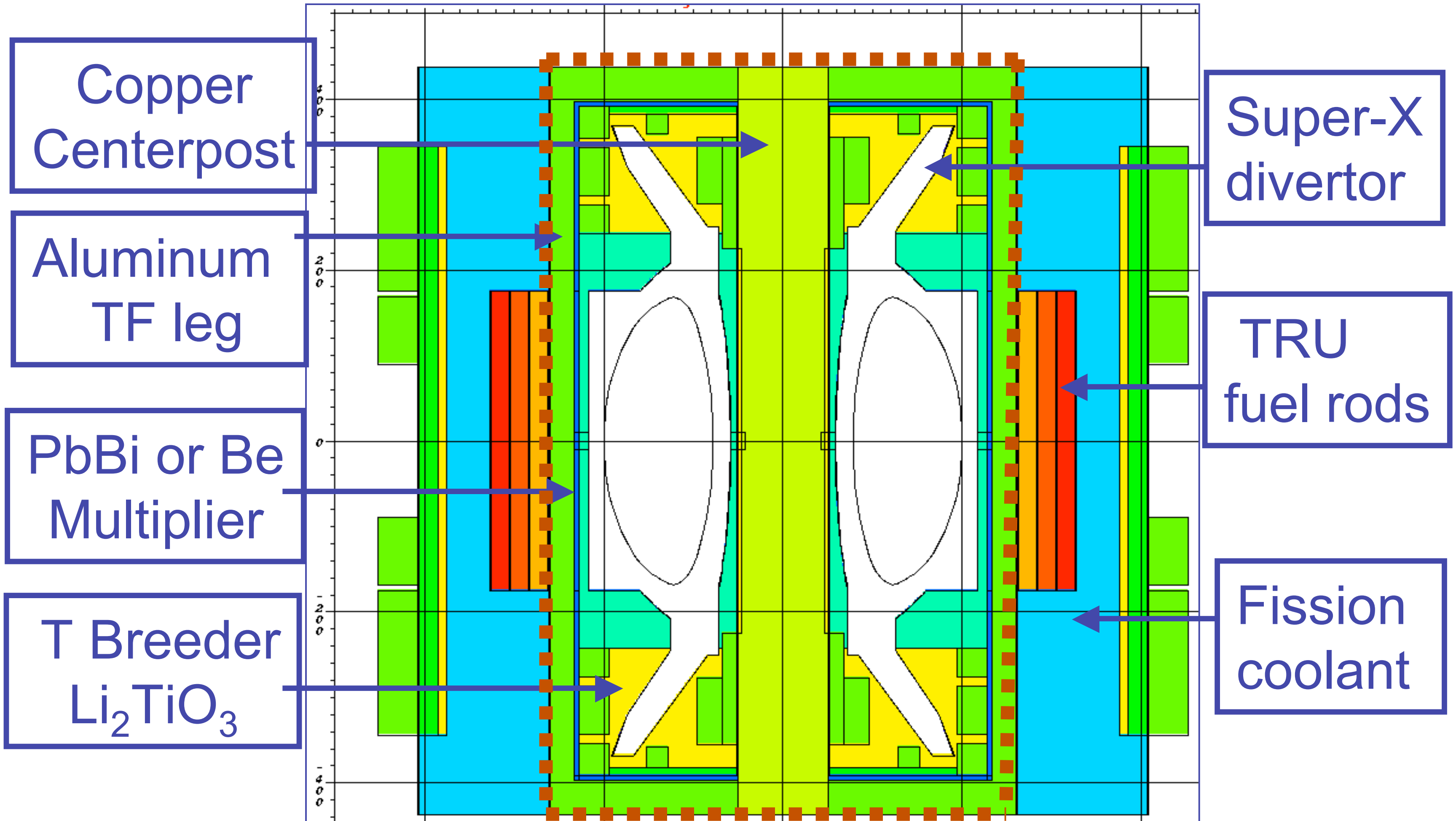
Generic and Texas Hybrids



For the GH
L ~ 8.5 m
For the TH
L ~3.2 m

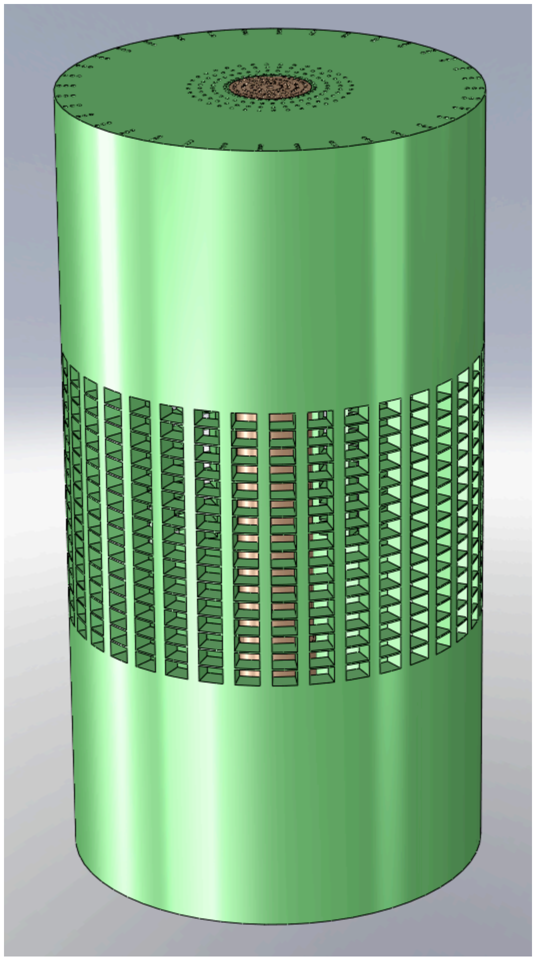
GH:Fission blanket (reactor core)is inside the magnetic field coils- strong mechanical and electromagnetic Fu-Fi coupling
TH:Fission blanket outside toroidal coils- fusion module removable- Fu-Fi coupling primarily neutronic

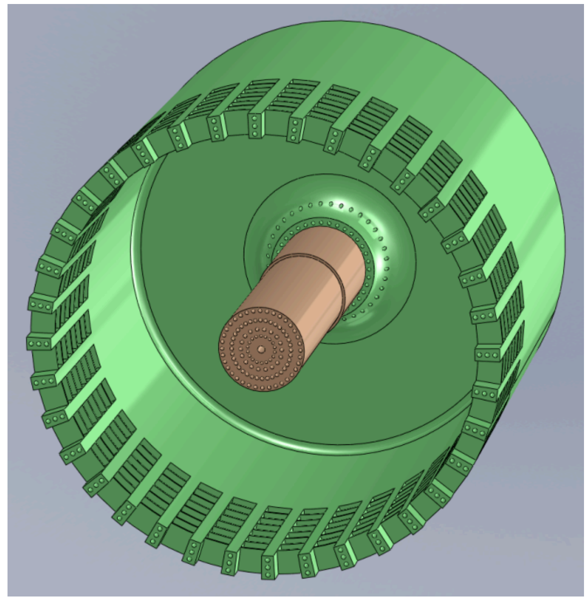
The Compact Fusion Neutron Source (CFNS): a self contained replaceable module

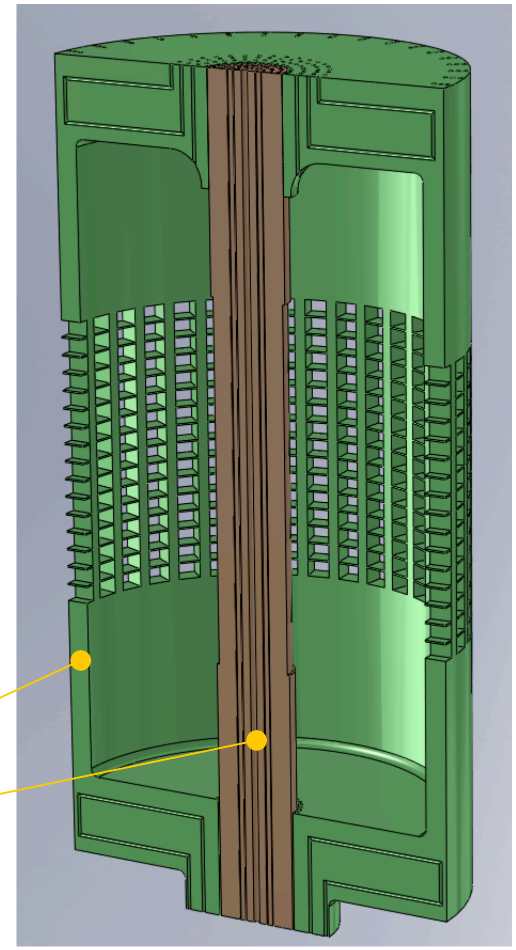


Compact Fusion Neutron Source drained: < 300 tons

Slotted outboard Toroidal Field magnets: allows neutron transport from plasma to fission assembly

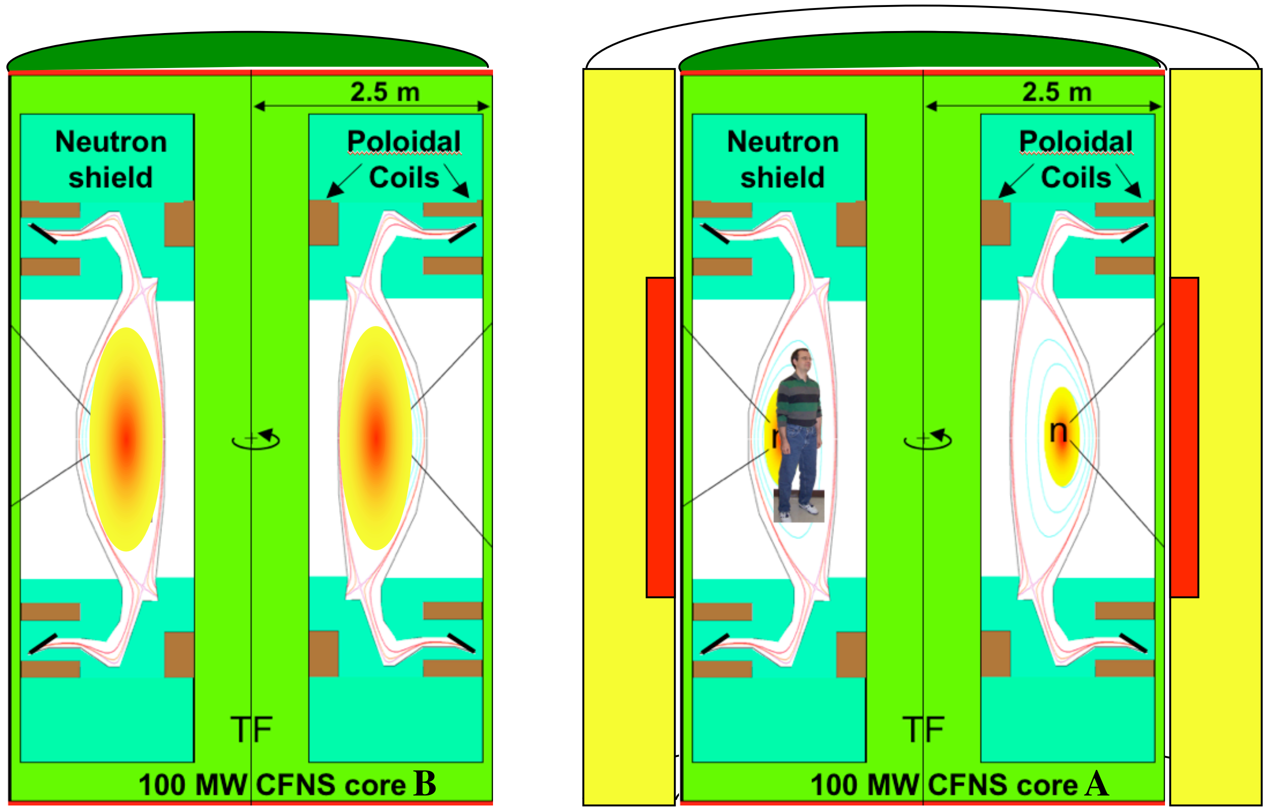






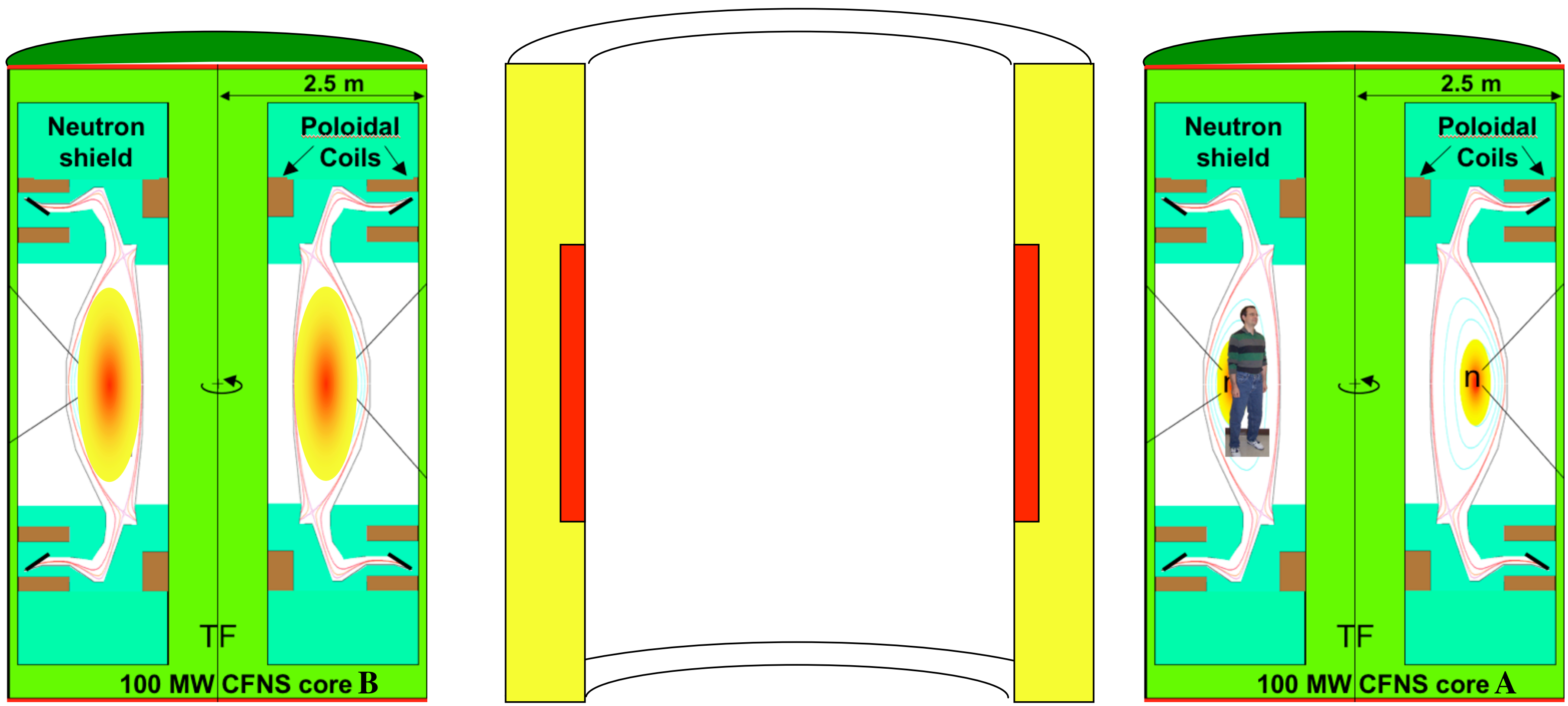
Replaceable Fusion Module Concept
Each hybrid has two CFNS units

- **SXD-insured compactness => CFNS fits inside the fission blanket**
- CFNS driver can be replaced every 1-2 full power years
- **CFNS driver itself is small fraction of cost, so a spare is affordable**



Replaceable Fusion Module

- **Pull CFNS driver A out to service bay once every 1–2 years or so**
-
- Refurbish driver A in service bay - much easier than in-situ repairs



Replaceable Fusion Module

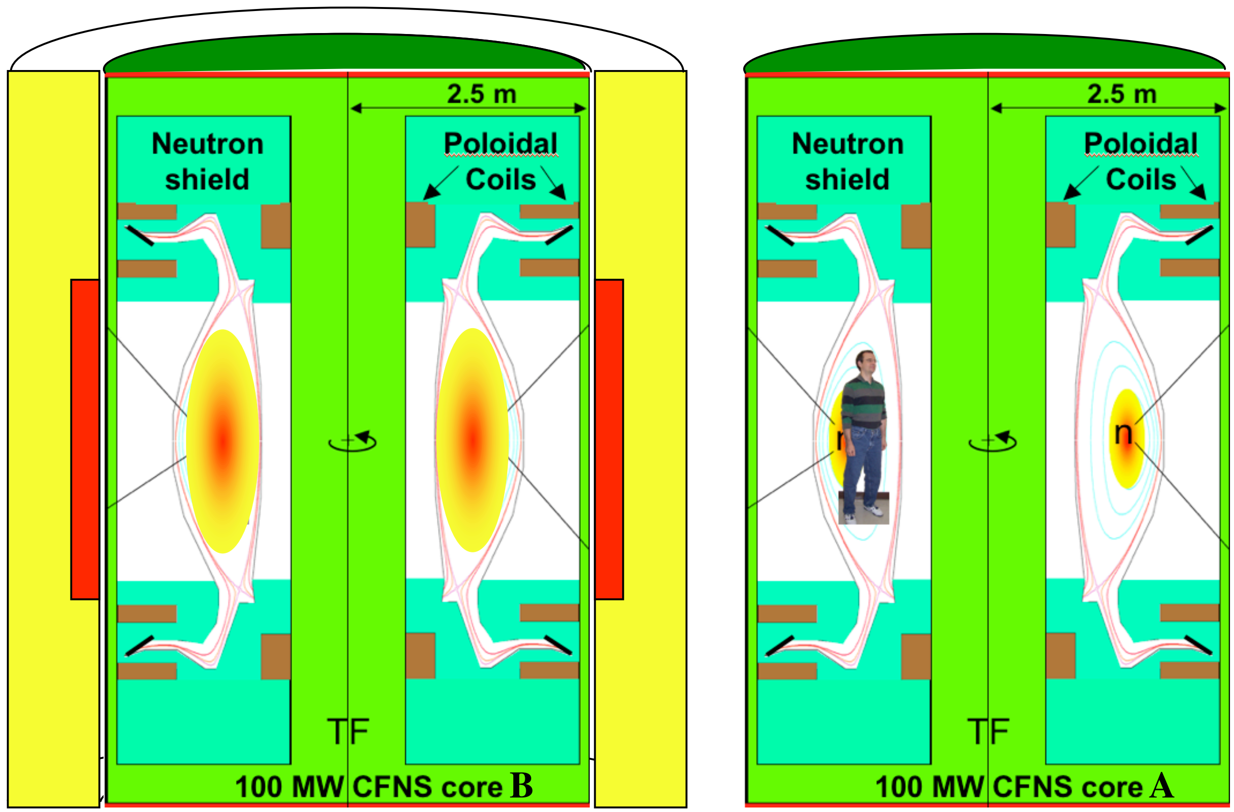
- **Put driver B into fission blanket**

- This can coincide with fission blanket maintenance

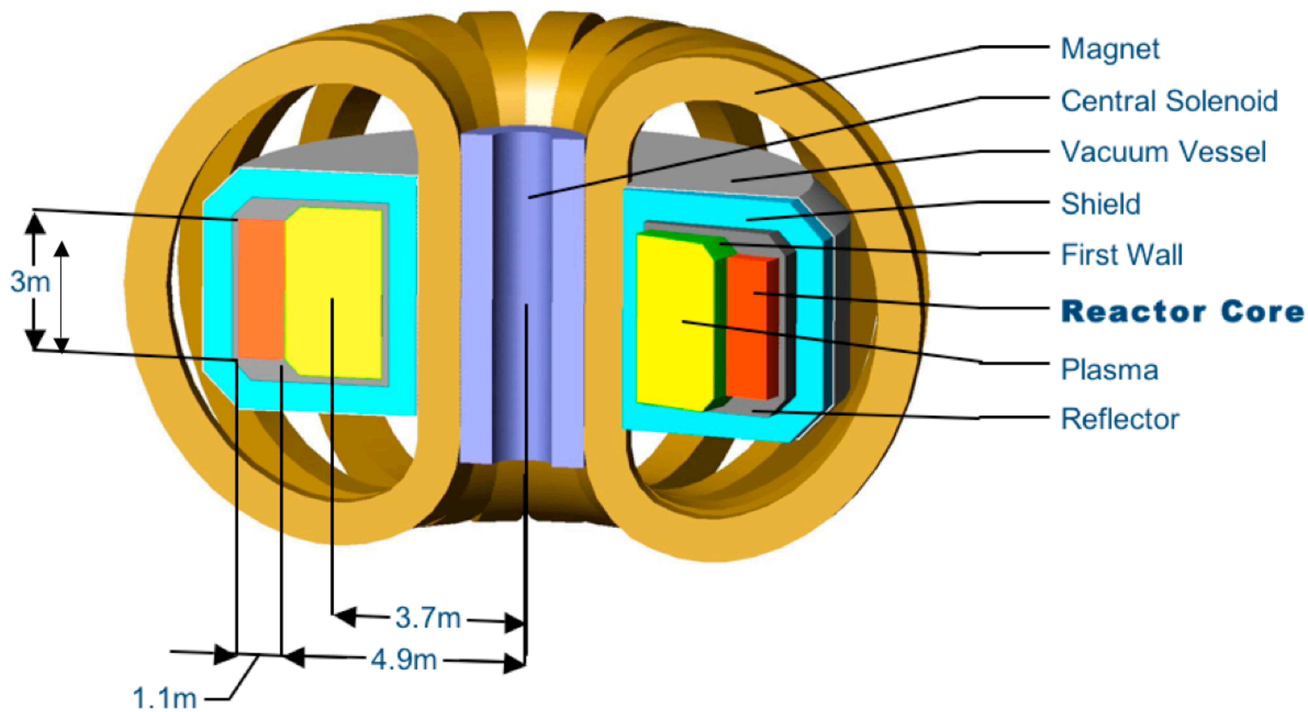
- Use driver B while driver A is being repaired

- In fusion reactor studies (ARIES) replacement of the fusion power core as a unit (~4000 tons) was adopted as the preferred approach (for devices similar to this)

- When not possible to replace as a unit, large segments (~ 800 tons) are often preffered



The Generic Hybrid



Large and Complex
Fusion and Fission systems intricately connected

Modularity / Replace-ability addresses MANY issues of the standard conception of a hybrid

- Fission blanket is not inside magnet coils or vacuum vessel *(fission blanket similar to a conventional reactor- both thermal/ fast spectrum studied)*

- Fission assembly is physically separate from fusion driver *(failure interactions minimized)*

- Fission blanket is outside vacuum TF coils *(otherwise strong magnetic effects on metal coolant is drastically reduced)*

- Fission assembly is electro-magnetically shielded from plasma transients by TF coils *(disruption effects greatly reduced)*

- Damaged driver refurbished in remote maintenance bay rather than in situ *(much faster turn-around of the fusion driver)*

- Each plant has two CFNS units- while one is used, the other is refurbished *(much less accumulation of damage from 14 MeV fusion neutrons)*

Fusion enables High Support Ratio fuel cycles a few hybrids needed to destroy waste

- The large majority of transuranics (TRU) can be incinerated in thermal spectrum reactors- we let them do this as the first step

- *However, most of the heat and very long term bio-hazard remain in the unburned residue*

- The hybrid is only used for this problematic residue- minor actinide isotopes (Am^{241}, Pu^{242}, Am^{243}, Cm^{244}, etc.)

  - *A concentrated residue of these isotopes is challenging to destroy in fission-only systems- both thermal and fast spectrum*

  - *External neutrons crucial here-we are working on several fuel cycles that favor hybrids*

Extra neutrons in the hybrid can allow greatly reduced reprocessing and destruction time

- Renewed interest in fuel cycles that greatly reduce reprocessing- *hybrids especially suited for such cycles*
  - Waste incineration with only one reprocessing step
  - Multi-reprocessing cycles with order of magnitude reductions in the TRU throughput (especially the weaponizable isotopes)
- External neutrons makes incineration feasible in a thermal neutron spectrum
  - *Cross sections are large, so rates of incineration are much larger*

How ready is magnetic fusion?

Tokamak Neutron Source Credibility

- **JET in 1997**: 16 MW attained transiently, ~ 22MJ/pulse
  - 1997 TFTR: 8-10 MW transiently, ~ 5 MJ/pulse
  - JT-60U (DT equivalent) similar to JET in 1998

- Devices in the coming decade: fusion power per pulse, about 1 pulse per day

  - JET upgrades better than 1997 ~ several 10's of MJ?
  - Long pulse K-STAR tokamak (300 sec) ~ 10^3 MJ (*DT equivalent*)
  - WENDELSTEIN 7-X (> 1000 sec) ~ 10^2-10^3 MJ (*DT equivalent*)
  - ITER: (400s MW for > 500 sec) > 2 x 10^5 MJ
  - **IFS CFNS for hybrid** **~ 10^7 MJ PER DAY**

CFNS: Conservative Fusion Physics Demands

- CFNS uses operating modes and *dimensionless physics parameters* where present experiments operate reliably (tokamaks & spherical tokamaks
- *A CFNS* ***is NOT an ignited plasma*** ***-*** *it is not necessary to await results of ITER*

Device	Normalized confinement H	Gross stability β_N	α power / heating power
Today's experiments- Routine operation	1	< 3	< 0.1
Today's experiments- Advanced operation	< 1.5	< 4.5	< 0.2
Hybrid - CFNS- FNF	**1-1.2**	**2-3**	**0.3-0.5**
ITER- basic	1	2	2
ITER-advanced	1.5	< 3.5	1-2
"Economic" pure fusion reactor	1.2 -1.5	4-6	4-10

CFNS for a hybrid is very similar to proposed fusion Component Test Facilities

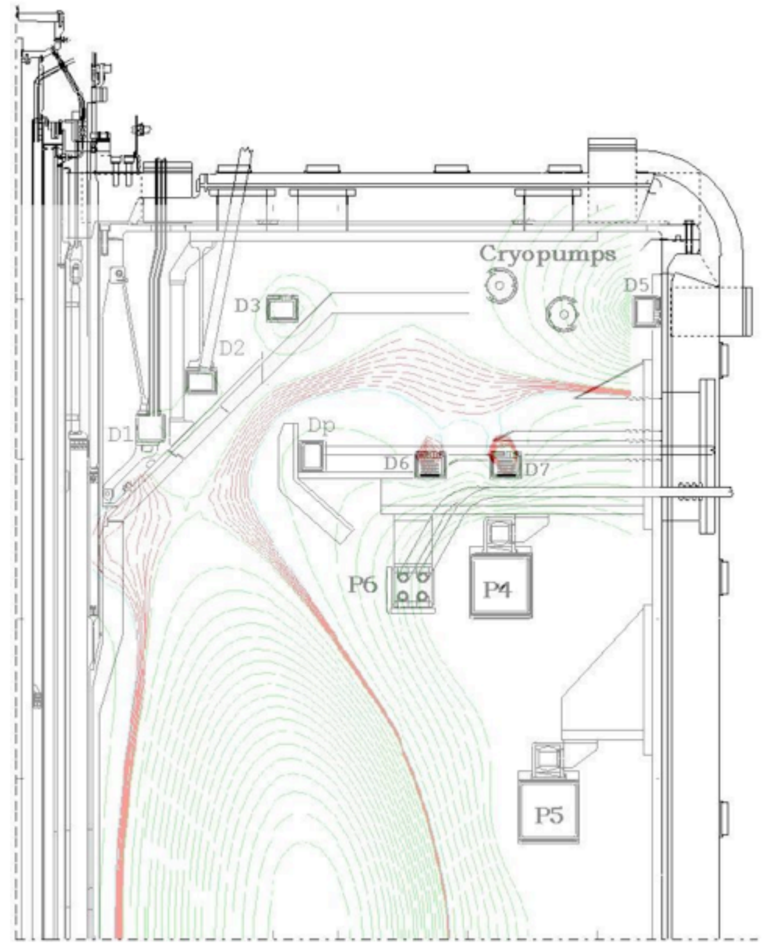
- CTF: considered in US and EU for 2020's as next fusion device
  - *A CTF is a prerequisite for <u>either a pure fusion reactor or the standard conception of a hybrid</u>*
  - Copper/Aluminum magnets to greatly reduce cost, device size (much more compact than superconducting coil devices)
  - CTF fusion power (~ 100-200 MW) with availability growing to 30%
  - Rapid replacement of large segments is a crucial element of CTF
- Hybrid CFNS- technical characteristics similar to early operation FNSF/CTF
  - CFNS availability *~ 40-45%* enables overall hybrid availability of *> 80%*
  - Aluminum outboard magnets with minimal shielding, ***reduces CFNS weight to < 300 tons***
  - *Neutron damage for a hybrid can be far less than for a pure fusion application*

Replaceable module concept: greatly reduces materials challenges from 14 MeV neutrons

- *UT hybrid: much less demanding requirements than CTF testing for DEMO*
  - Hybrid Neutron wall fluence as low as ~ 1-2 MW yr / m^2
  - CTF testing prior to pure fusion DEMO ~ 6 MW yr / m^2
  - Pure fusion DEMO ~ 10 MW yr / m^2
- *Component damage for UT hybrid- potentially many times less*
  - Testing iterations at 1-2 MW yr/m^2 are much faster
  - Less material / design development and iterations likely needed
- *A quicker, less risky journey to a practical application for fusion*
- Have examined neutron damage and heating of the magnets

Super-X divertor solves the exhaust problem
Enables a compact high power density CFNS

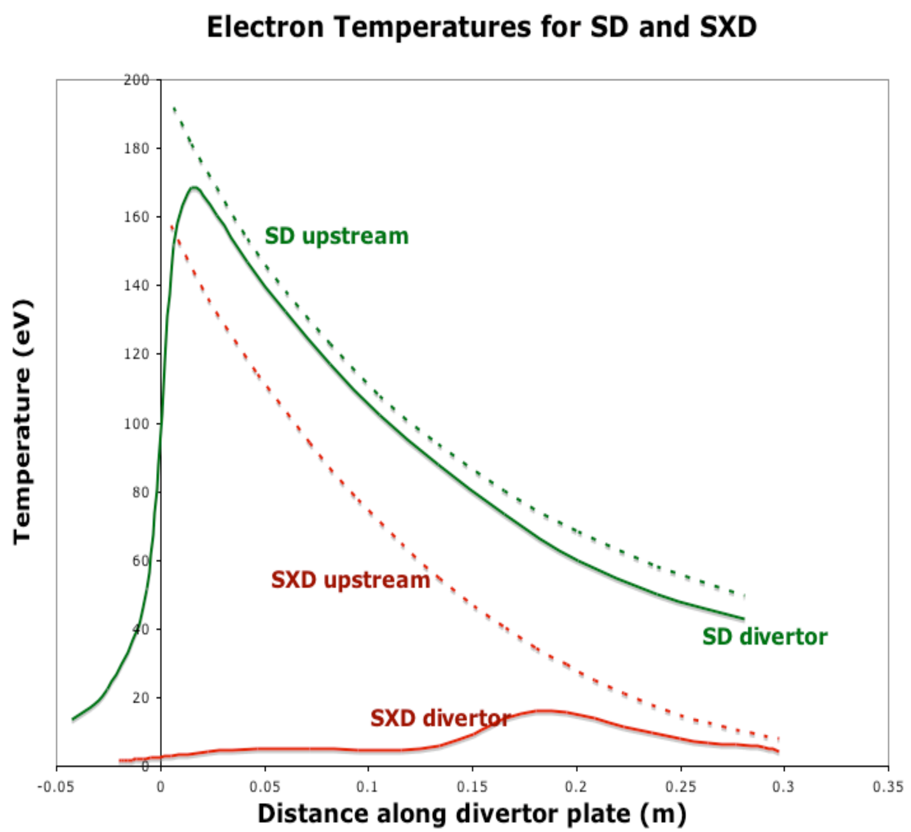
- **Worldwide plans are in motion to test SXD:**
  - MAST upgrade now includes SXD, now funded
  - Long-pulse superconducting tokamak SST in India designing SXD
  - NSTX: XD planned, and SXD in the future
  - US Spherical tokamak CTF has adopted SXD as the reference divertor



SXD for MAST Upgrade

Super-X Divertor (SXD) provides the desired operation - unlike the standard divertor

- SXD -Magnetic geometry is changed so exhausted hot plasma expands and cools
- Analysis using best available simulation (SOLPS - as for ITER)
- *Standard divertor - exhausted high power plasma is unacceptable*
  - "sheath limited"- very hot and damaging
- *SXD- exhausted plasma is desirable*
  - "partially detached"- what ITER design aims for
  - T < 10- 20 eV



Is a compact normal coil device workable?

Cost of various CFNS components

- *Unlike the 22,000 ton ITER, the cost of the ~300 ton, non super-conducting CFNS is a very small part of the total fusion cost:*

RF heating/ CD sources	$ 200-500 M
Remote handling & ancillaries	$ 200 M
Device cooling	$ 100 M
Power supply & Control	$ 100 M
Facilities & equipment	$ 250 M
Total	$850-1150 M

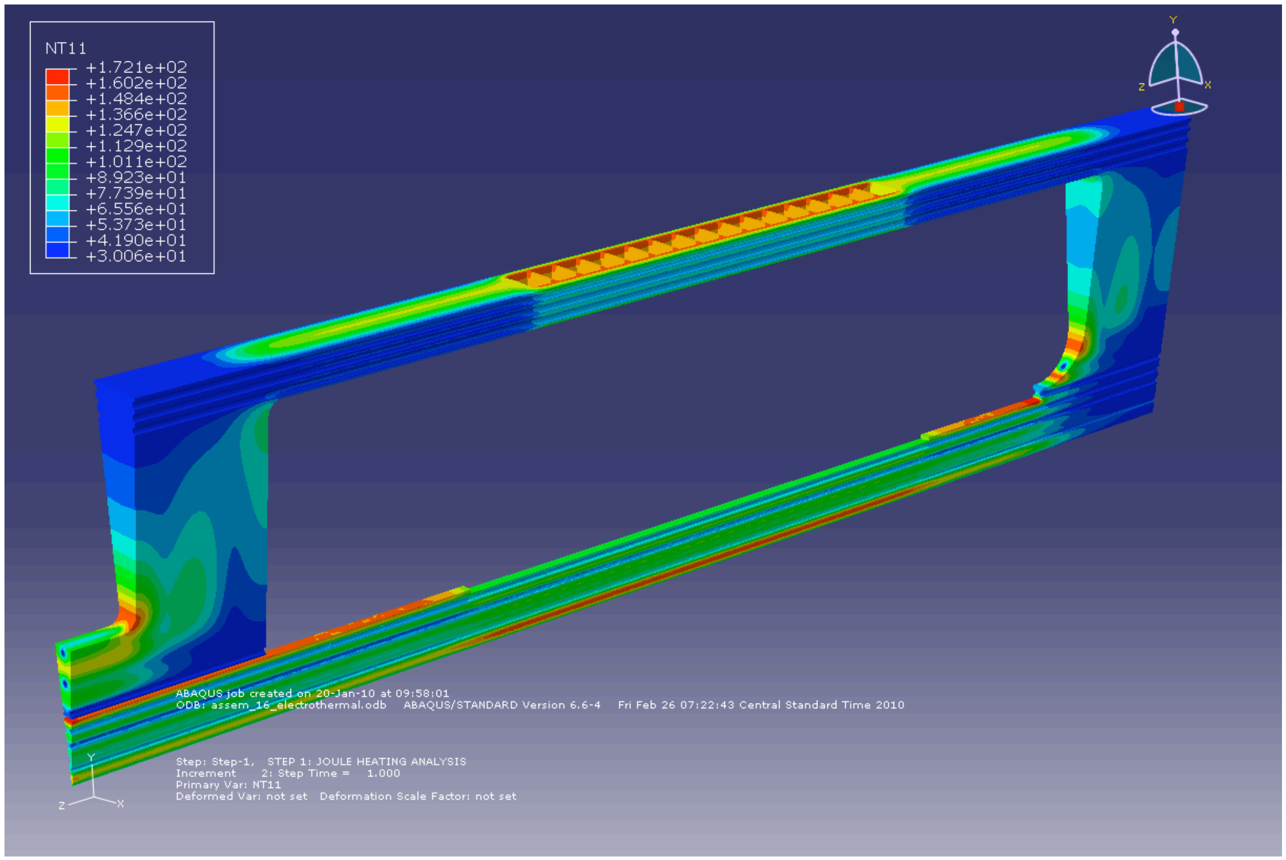
One CFNS unit < $ 220 M

- Hence, we believe the advantages in higher plant availability far outweigh the cost disadvantage of having two CFNS

- *The CFNS is by far the component with the greatest cost uncertainty, but the uncertainty of the total cost is likely much less*

- Cost of frequently replaced components ~ $14 M

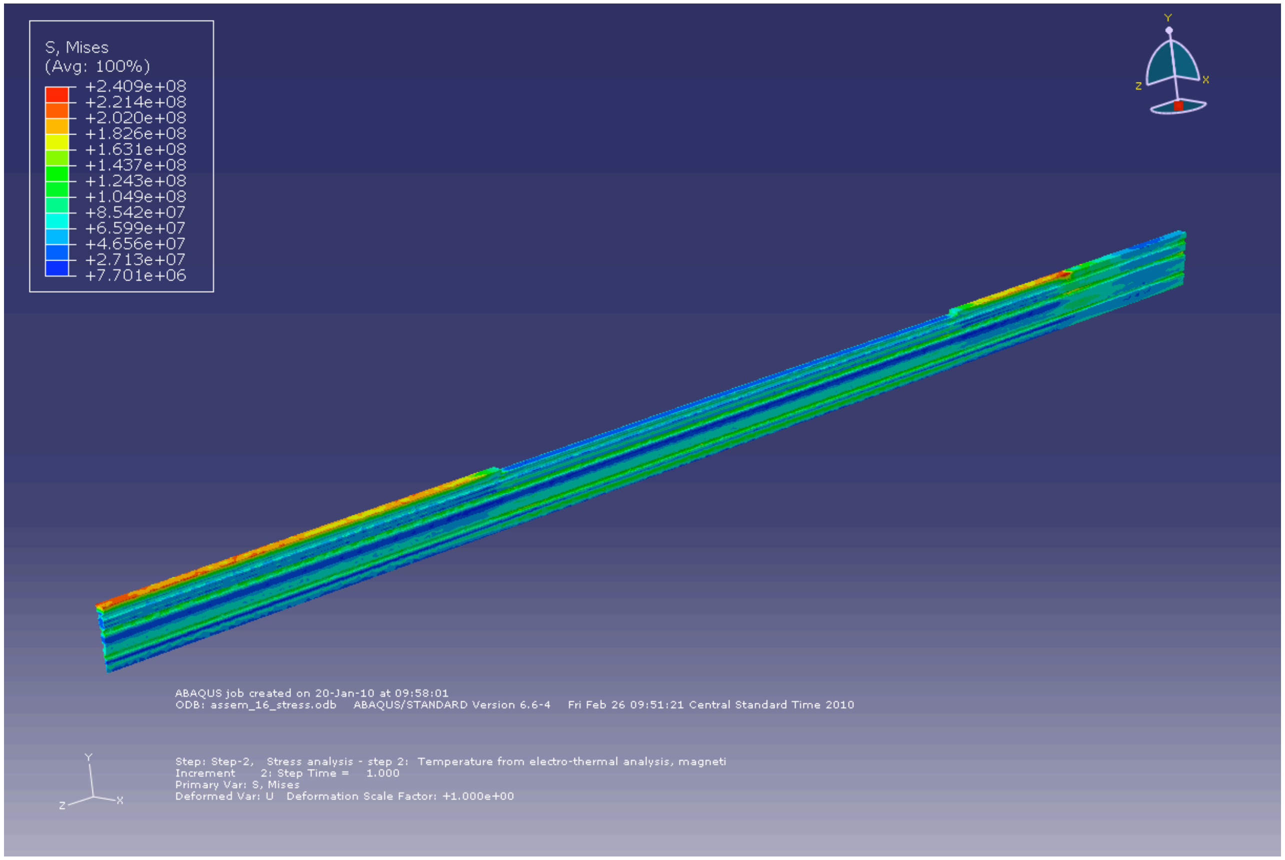
Electro thermo-hydraulic analysis – temperature of magnet segment



Fusion Neutron Damage- Cu Centerpost

- Employ 10 cm neutron shield of steel / H_20
  - Roughly comparable to fusion reactor studies with Cu magnets
- Maximum Cu damage rate: < 5 dpa/FPY
  - Cu temperature < 150 C, but as low as ~30 C near coolant channels
  - Substantial embrittlement near water cooling channels
- Are stresses low enough for this to be tolerable?
- ITER design rules for brittle material indicate it is

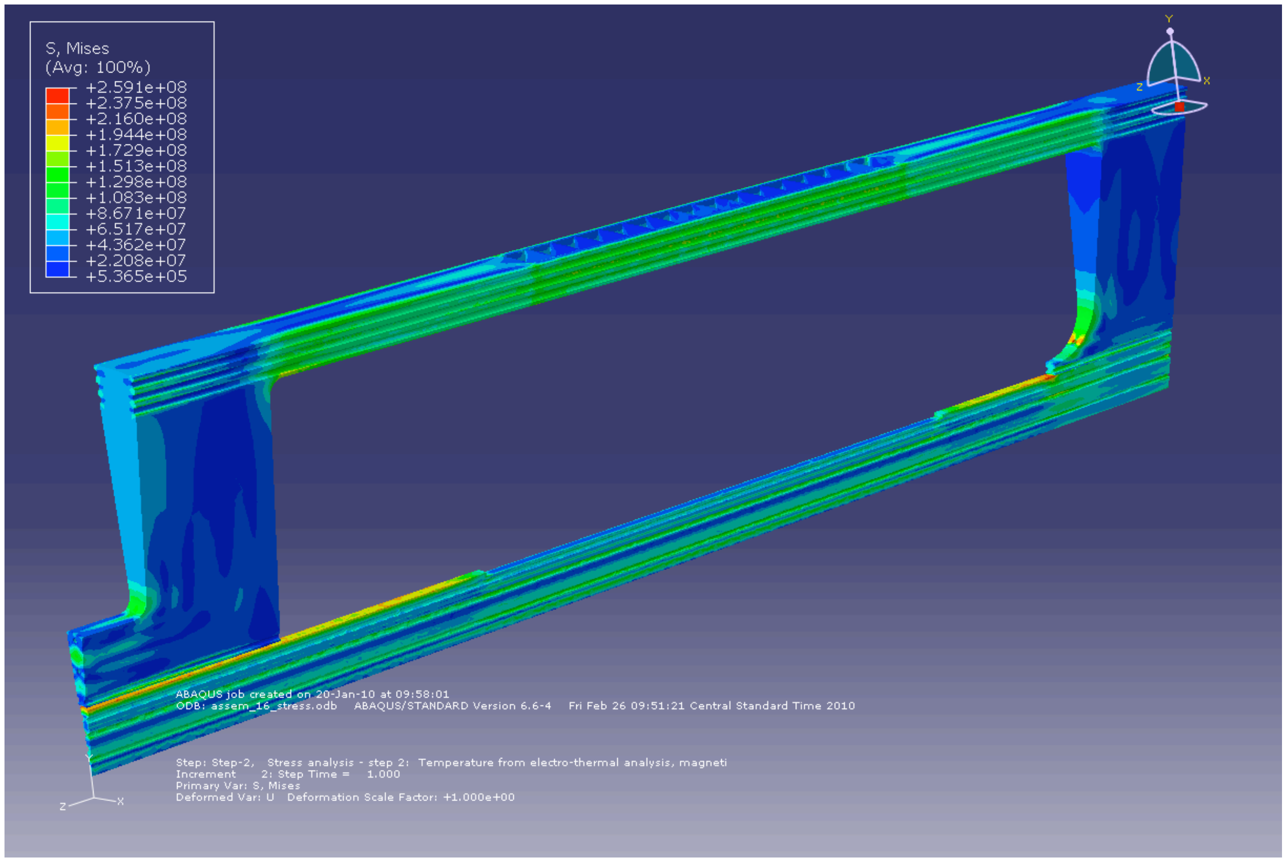
Stress in center post



Stress- Centerpost

- Max stress (primary plus secondary) in embrittled region < 200 Mpa
- ARIES reactor study: estimated maximum tolerable stress of 260 MPa for embrittled Cu
    - Expect CFNS is also below ITER guidelines, but further analysis is needed

Stress analysis – stress due to interference, temperature, magnetic



Stresses in outboard Al magnets

- Primary plus secondary stresses less than roughly 50% of yield stress
- Radiation heating, though < 20% of Ohmic heating, is yet to be included
- Outer steel shell (included in MCNP) expected to reduce stress in Al magnets to ~ 25% of yield
- Neutron damage effects appear modest but require further analysis

Neutron Damage-
Vacuum vessel and Aluminum outboard magnet

- Damage levels likely allow a multi-year lifetime for vacuum vessel and Outboard TF magnets

- Lifetime of plasma chamber first wall is more uncertain due to very high He production

Damage per full power year (fission and fusion neutrons)

	dpa	appm He
Steel facing plasma	11-14	80-120
Steel vacuum vessel (outboard)	6.3	20
Steel fuel rod cladding	10-11	1.3 (8)
Aluminum outboard magnets	11-20	20-60

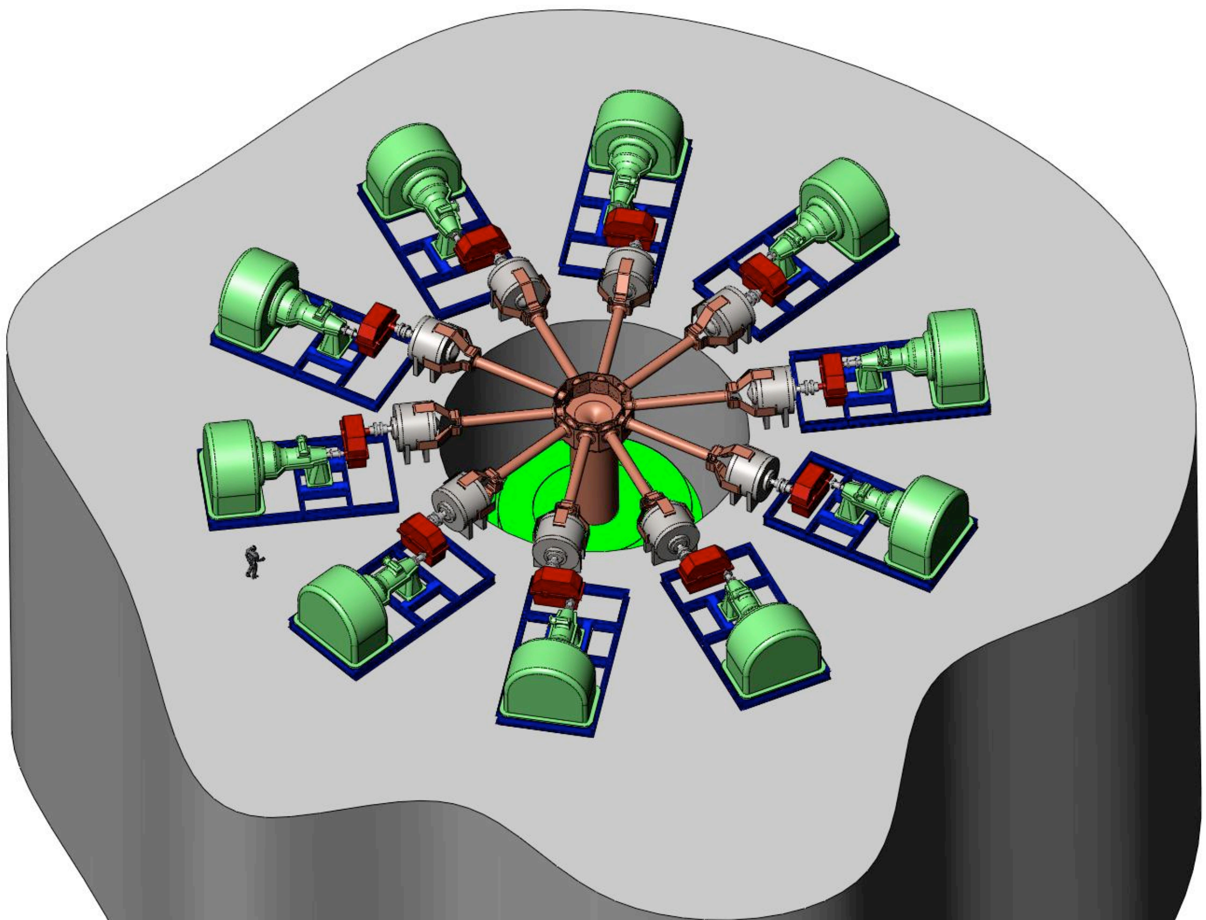
appm limit for fusion materials thought to be in the several hundreds

Magnet power supplies

- Scoping studies indicate that homopolar generators are the most compact, least expensive power supply option (18 MA, < 10 V)

- Existing brush technology should have acceptable life for this low speed application

- They should also have much better radiation tolerance than semiconductor supplies



Neutron considerations and fuel cycles

Our strategy for a hybrid

- Fission energy has worked very hard to demonstrate commercially desirable, practical energy sources (and will continue to do more!)

- Fusion is the newcomer- introduce fusion gradually into the nuclear energy picture

- We have emphasized fuel cycles with a small near term fusion power source, and a relatively small number of hybrids-

  We emphasize a high support ratio of hybrids to pure fission plants

- For modest fusion power levels (~ 100-200 MW) the highest hybrid support ratios are possible for hybrids that destroy waste from fission reactor using enriched U fuel

High support ratio fuel cycles

- Allow commercially successful reactors to destroy most of their own waste (in terms of TRU mass)- easy isotopes like Pu^{239}, Pu^{241}, etc.

- Use hybrids to destroy the relatively small residue- isotopes that are
  - *Difficult for fission-only systems to incinerate* (minor actinides, Pu^{242})
  - Most geologically problematic- *they contribute most of the heat and radio-toxicity for time > 100,000 years*

- Also, there is renewed interest in fuel cycles that greatly reduce reprocessing- *hybrids especially suited for such cycles*
  - Waste incineration with only one reprocessing step
  - Multi-reprocessing cycles with order of magnitude reductions in the TRU throughput (especially the weaponizable isotopes)

Specific fuel Cycles

- Assume reprocessing step of each LWR fuel load
  - *When possible- no more reprocessing in the hybrid*

- Burn most TRU in thermal spectrum system
  1. Deep burn in one pass in LWR using Inert Matrix Fuel (IMF) (~ 60-75%)
  2. Deep burn in one pass in TRISO based High Temperature Reactors (HTRs)
  3. Burn Pu and Np in LWRs with multi-recycle, leave minor actinides for hybrid

- Use the hybrid for unburned residual TRU of 1-3

- *Recent interest- can we avoid fast spectrum fission technology altogether, and base the hybrid on the same technology as commercial thermal spectrum reactor*

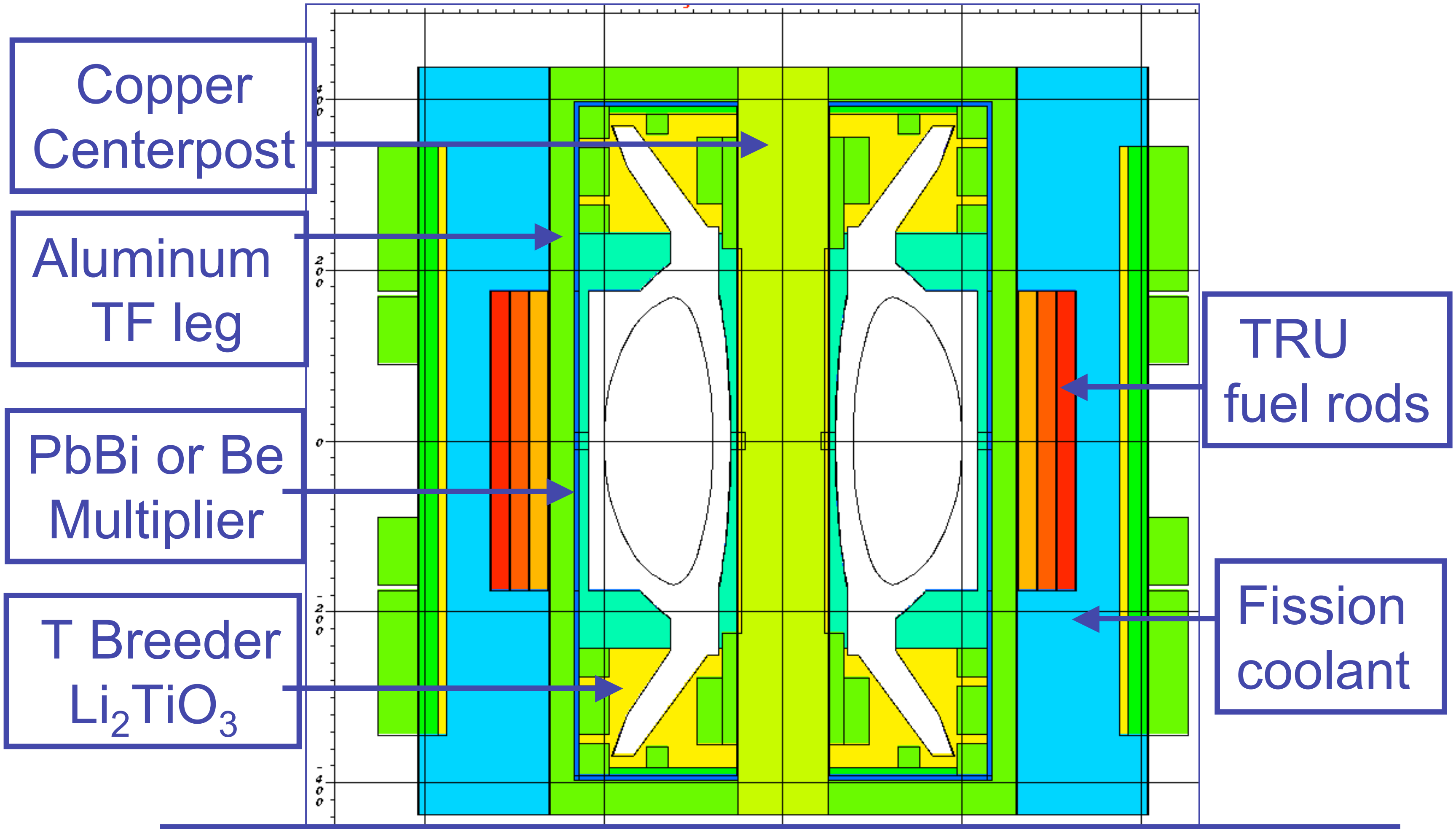
Fission partners to the CFNS

- Fast spectrum, liquid metal fission blanket
  - multi-recycle to final destruction
  - Hybrid fuel cycles reduce TRU reprocessing throughput by an order of magnitude compared to conventional fission-only Fast Reactor (FR) cycle

- *Thermal spectrum blanket- present preferred choice*
  - TRISO based, liquid salt cooled
  - Heavy water moderated blanket- like commercial reactors in India and Canada

- *Thermal spectrum allows one pass through the hybrid with rapid destruction, and high levels of destruction with no hybrid reprocessing*

Schematic of MCNP layout



Three or four zone resuffling in the fission blanket

Support Ratios

Number of hybrids per 100 thermal spectrum reactors (LWR or HTR)

	Conventional DOE Fast reactor fuel cycle	LWR deep burn with 1-2 pass IMF Hybrid for residue	Deep burn in HTR TRISO hybrid for residue	Pu and Np burned in LWR Minor actinides burned in Fast Reactor	Pu and Np burned in LWR Minor actinides burned in hybrid
Fission-only fast reactor	30-40	-	-	12	-
Hybrid	-	6-10	10	-	2-5

Conclusions

- Appears like a lot of results from three impoverished theoretical physicists –did get help from kind engineers

- Here is a pre-conceptual design for a desirable, near term hybrid:

- Compactness, modular and low cost replaceable CFNS thanks to the Super-X divertor

And

- Several fuel cycles for waste destruction made attractive and possible by a copious supply of fusion neutrons